

# Temporal electrical response of chiral smectic liquid crystal displays with V/W-shaped electrooptical characteristic

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*Chiral smectic liquid crystal cells showing V-shaped electrooptical switching have been reported as one of the most promising technologies for high-end display applications. In this work, time-resolved electrical behaviour of these devices has been obtained through a set of systematic measurements. The electrical equivalent circuit has been derived, a number of simulations at different frequencies have been performed using commercial software for analogue circuits. Performance of this electrical model to account for time domain variations of switching currents in chiral smectic LC displays with V/W-shaped electrooptical response has been analyzed as well.*

**Keywords:** electrical response, non-linear capacitor, switching current, chiral smectic liquid crystal, V/W-shaped electrooptical response.

## 1. Introduction

Since V-shaped switching in chiral smectic liquid crystals was reported [1], a high number of investigations have been performed to explain its origin and to analyze its electrooptical behaviour [2]. These materials have many advantages of ferroelectric liquid crystals (FLC) like fast response time, wide viewing angle and good contrast ratio. Besides, chiral smectics LCs with V-shaped electrooptical response show thresholdless switching, dramatically reducing switching voltage down to voltage levels that can be managed by standard CMOS drivers. This feature made them excellent candidates for display applications. However, under different conditions of alignment conditioning, cell thickness, temperature, and driving frequency, V-shaped switching may become W-shaped [6]. Although specific driving schemes managing displays with V-shaped and W-shaped electrooptical response have been proposed and demonstrated, the presence of variable W-shaped response may impair the display performance since the position of the dark state becomes variable, depending on external factors such as working temperature and frame rate.

Time-resolved electrical simulation of these devices can be useful to improve the design of driving schemes and to optimize their dynamic behaviour. In this work, switching currents have been systematically measured at different frequencies, for thresholdless switching (also called

V-mode) of chiral smectic LC displays. Electrical equivalent circuits (EEC) describing such behaviour have been derived, and time domain simulations of EECs have been compared to experimental data in order to validate the approach. These electrical simulations have been performed using commercial software for analogue circuits' simulation. Analogous studies to deduce electrooptical behaviour of V-W- mode LC cells propose a more detailed computer model based on a numerical procedure

## 2. Experimental

A set of frequency-dependent measurements of switching currents were performed in order to study the electric behaviour of smectic liquid crystal cells with either V or W-mode electrooptical characteristic. An A/D instrumentation system allowing us to measure low switching currents and electrical polarization in a wide range of frequencies was designed and implemented. A complete description of this electronic system is given elsewhere [9]. Monopixel samples having an electrode area of 1×1 cm and a thickness of 1.8  $\mu\text{m}$  under surface-stabilized conditions were employed. Rubbed nylon was used as alignment material in both plates, assembled in a parallel configuration. An experimental LC mixture manufactured by the Military University of Technology was used in these electrical tests. All experiments were developed at 27°C.

A method to obtain the EEC for smectic liquid crystal cells with V or W-mode electrooptical response was de-

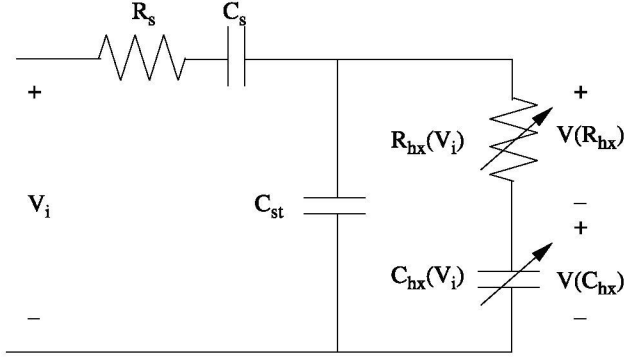


Fig. 1. Electrical equivalent circuit of V/W-mode chiral smectic liquid crystal cells.

scribed in a previous work. This method was based on AC impedance spectroscopy. Using this technique, fitting of experimental data values can be used to derive passive elements of the EEC (Fig. 1) whose structure was proposed elsewhere. Each element or combination of elements describes the different aspects related to the electric and optical responses:

- the static capacitor  $C_{st}$  accounts for the nonferroelectric part of the dielectric response (due to instantaneous polarization) of the V or W-mode LC device,
- the series combination  $R_{hx}-C_{hx}$  deals with the ferroelectric aspect of the dielectric response, these two elements take into account the dielectric relaxation (heat dissipation) and the slow orientation of dipole polarization, respectively,
- the series combination  $R_s-C_s$  reflects the influence of technological parameters of the cell such as resistivity and capacity of insulating, aligning, and ITO layers.

Once the values of the EEC elements for the V/W-mode cell were derived, the EEC time-domain electrical behaviour has been calculated, using commercial software for analogue circuits (Orcad Pspice).

### 3. Results and discussion

Figure 2 summarizes the results obtained for the EEC elements of one of the samples under study. As seen in the figure,  $R_s$ ,  $C_s$ , and  $C_{st}$  have constant values while  $R_{hx}$  and  $C_{hx}$  show a nonlinear dependence with voltage applied to the cell. For a nonlinear voltage-dependent capacitor, the following relationship can be derived

$$i(C_{hx}) = C_{hx}(V(C_{hx})) \frac{dV(C_{hx})}{dt} \quad (1)$$

where  $i(C_{hx})$  and  $V(C_{hx})$  are electric current and voltage across the capacitance  $C_{hx}$ , respectively. This relationship can be used in this case, where the capacitance was measured at different bias voltages. In a similar way, electric current across the voltage-dependent resistance  $R_{hx}$  can be obtained as follows

$$i(R_{hx}) = \frac{V(R_{hx})}{R_{hx}(V(R_{hx}))} \quad (2)$$

where  $i(R_{hx})$  and  $V(R_{hx})$  are the electric current and voltage across the resistance  $R_{hx}$ , respectively.

In this approach, the variation of  $C_{hx}$  and  $R_{hx}$  with voltages across them is unknown. Nevertheless, the variation of both elements of the EEC with the applied voltage  $V_i$  has been derived (Fig. 2).

In this kind of devices, the optical transmission can be deduced from electric induced polarization, associated to dipole polarization reorientation. This reorientation can be appreciated if a sufficiently low frequency input voltage is applied. In this case, the contribution of  $R_s$  and  $R_{hx}$  in the temporal electrical behaviour of EEC can be neglected.

This fact has been corroborated by simulation results. In this case, only capacitive elements of EEC should be considered. With this approach, a relationship between  $V_i$  and  $V(C_{hx})$  can be derived as follows

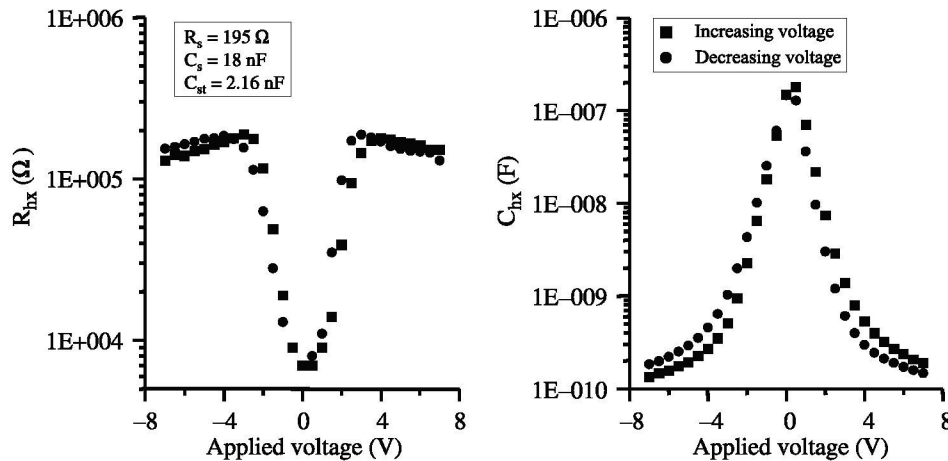


Fig. 2. Variation of nonlinear elements of electrical equivalent circuit ( $R_{hx}$  and  $C_{hx}$ ) as a function of voltage for the V/W-mode LC sample under study. Note that several elements are taken constant. A low-frequency triangular waveform is being applied to the cell.

$$V(C_{hx}) = V_i \frac{C_s}{C_s + C_{st} + C_{hx}(V_i)} \quad (3)$$

Therefore, dependence of the variable capacitor  $C_{hx}$  with the voltage across it can be described in low frequency regime.

The nonlinear dependence of the capacitance  $C_{hx}$  with the voltage  $V(C_{hx})$  has been implemented with an analogue behavioural model, using a voltage-dependent current source. The simulation also includes two leakage resistances in the EEC, in parallel with  $C_s$  and  $C_{st}$ , respectively. These leakage resistances are necessary to account for the EEC behaviour at low frequencies. Values of both resistances have been derived from the simulation ( $R_{p1} = 30 \text{ M}\Omega$ ,  $R_{p2} = 150 \text{ M}\Omega$ ). The final simulated EEC is displayed in Fig. 3.

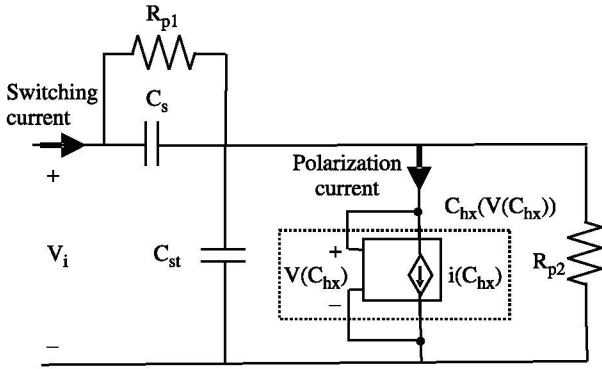


Fig. 3. Simulated electrical equivalent circuit of V/W-mode chiral smectic liquid crystal cells including a voltage-dependent current source and leakage resistances.

A fair agreement has been found between simulation results from EECs obtained for the V/W-mode cells and experimental switching currents measured at different low frequencies. Figure 4 shows simulated and experimental switching currents for triangular waveforms from 100 mHz to 5 Hz. Maximum values of electric currents are obtained when the applied triangular waveform crosses through the zero volts level. Agreement between simulation results and experimental data for the switching current decreases as frequency decreases. This might be attributed to secondary contributions to the whole current which are not included in the proposed EEC.

On the other hand, it is possible to derive the optical transmission characteristic of the LC cell with V/W-shaped electrooptical response from its temporal electrical behaviour. Placing the cell between crossed polarizers, with the optical axis of input polarizer parallel to the normal of the smectic layer in the input side of the LC sample, the optical transmission  $T$  can be calculated, assuming a constant retardation, as follows

$$T = T_o \sin^2(2\theta) \quad (4)$$

where  $T_o$  is the maximum possible transmission, that is, transmission between parallel polarizers and  $\theta$  is the apparent tilt angle that varies with voltage applied to the cell.

Assuming that molecular director of LC rotates in the cone, the apparent tilt angle can be approximately calculated as follows

$$\theta = \theta \frac{P}{P_s} \quad (5)$$

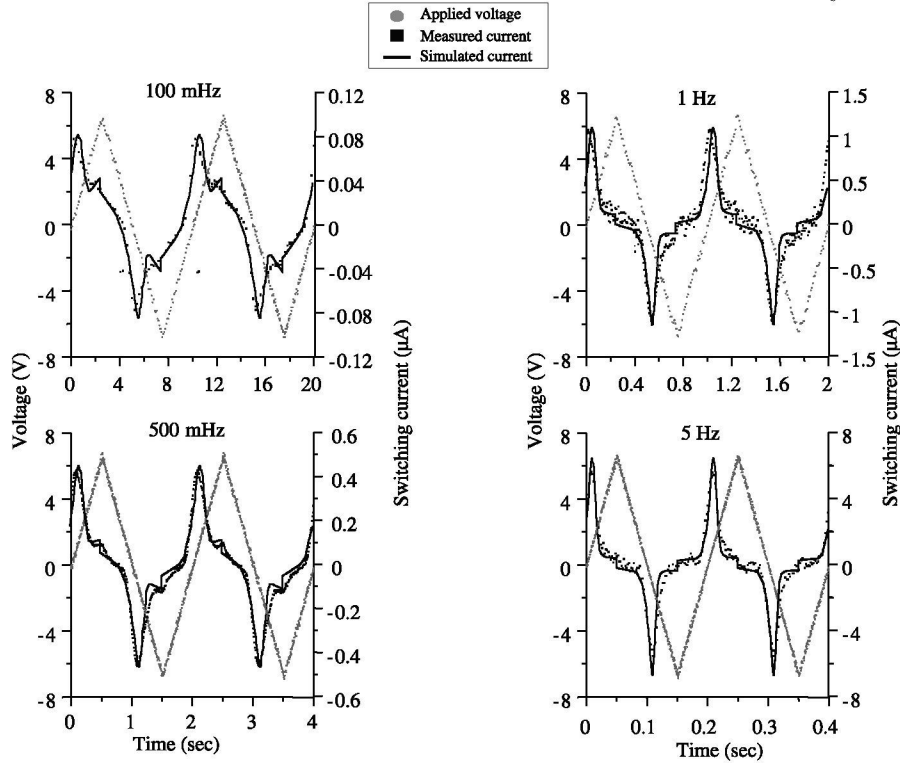


Fig. 4. Measured and simulated switching currents for triangular waveforms with frequencies of 100 mHz, 500 mHz, 1 Hz, and 5 Hz applied to the V/W-mode LC cell.

where  $\theta$  and  $P_s$  are the cone angle and spontaneous polarization of LC, respectively, and  $P$  is the electric induced polarization that can be obtained from electrical simulation of EEC in the following way

$$P = \frac{\int_t i(C_{hx}) dt}{A} \quad (6)$$

being  $A$  the effective area of the LC sample.

Results of simulation made for triangular waveforms from 100 mHz to 5 Hz applied to the LC cell are represented in Fig. 5. As it can be seen, there is a reasonable

agreement between measured and simulated optical transmissions in the whole range of frequencies checked.

This information may be useful when designing drivers to address this kind of devices, since power consumption considerations play an important role for most suitable applications of LC devices with V/W-shaped electrooptical response.

#### 4. Conclusions

Optimized values for linear and non-linear passive elements of the electrical equivalent circuit of a chiral smectic

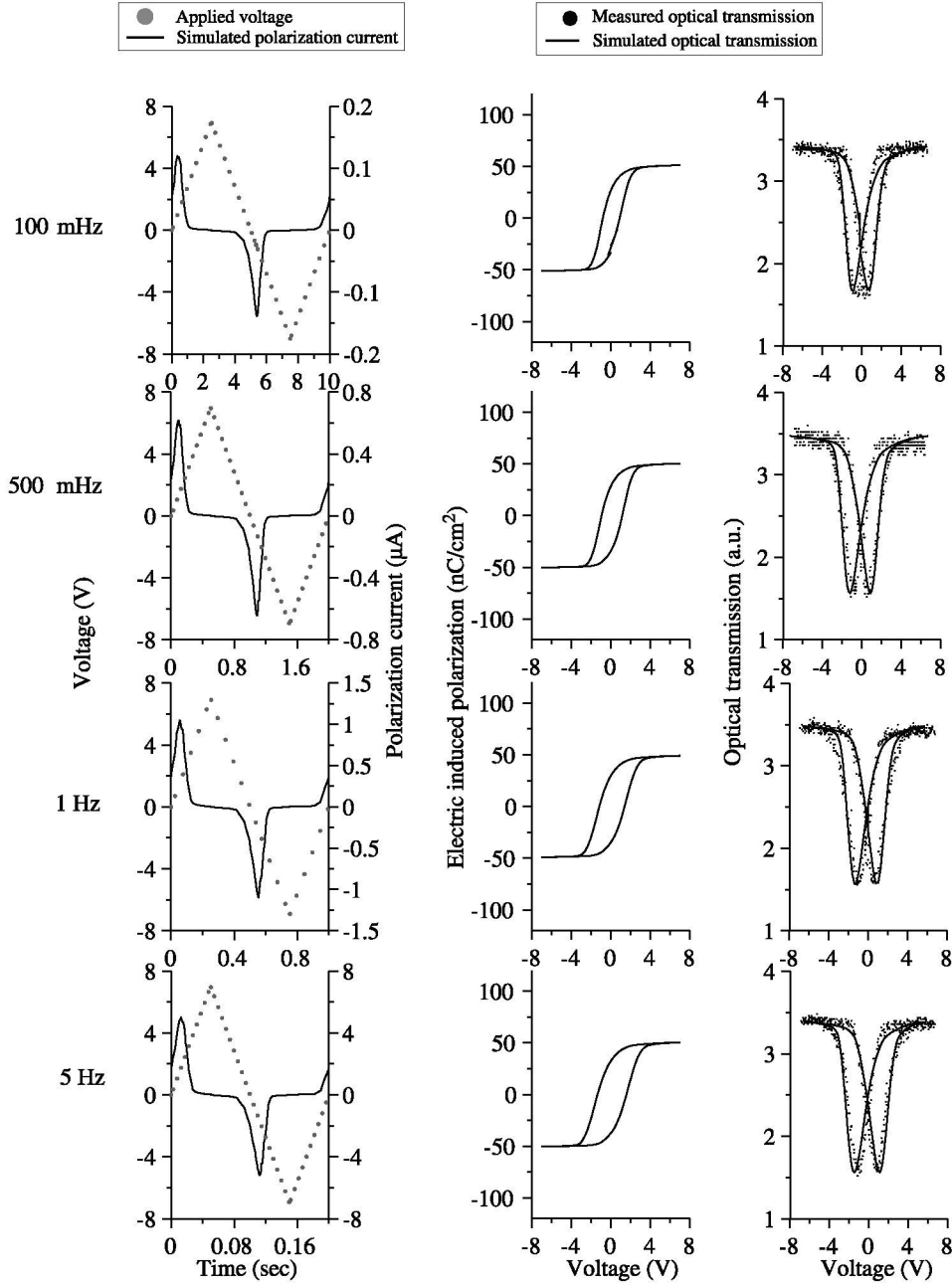


Fig. 5. Results of simulation for input triangular waveforms of 100 mHz, 500 mHz, 1 Hz, and 5 Hz. Current intensity through  $C_{hx}$  (polarization current) (left column), electric induced polarization (middle column), and comparison between measured and simulated optical transmission (right column).

LC cell with V/W-shaped electrooptical response have been calculated and compared to experimental results. These results were obtained by applying the AC impedance spectroscopy technique as experimental procedure, model values were optimized by a fitting process. The variation of nonlinear elements  $R_{hx}$  and  $C_{hx}$  as a function of the applied voltage has been obtained as well. The capability of the described electrical model to account for time domain variations of switching currents in V/W-mode chiral smectic LC displays has been demonstrated. Amplitude and shape of the electric current in the time domain of smectic LC displays provide useful information to determine the electro-optical performance of the whole display in actual working conditions.

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